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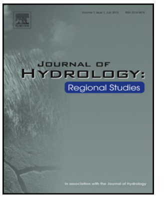

Quantifying the potential effects of high-volume water extractions on water resources during natural gas development: Marcellus Shale, NY

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A B S T R A C T

Study region: The Marcellus Shale, New York State, USA.
Study focus: Development of natural gas resources within the Marcellus Shale will require large volumes of water if high-volume hydraulic fracturing expands into New York State. Although this region has ample fresh water resources, it is necessary to explore the response of hydraulically connected groundwater and surface water systems to large withdrawals. Because such effects would not be apparent from a typical water budget approach, this study applied groundwater flow modelling under scenarios of high-volume water withdrawals. Emphasis on water quantity, in contrast with other lines of research concerning water quality, introduced an important perspective to this controversial topic.
New hydrological insights for the region: The potential effects of the withdrawal scenarios on both the water table and stream discharge were quantified. Based on these impact results, locations in the aquifer and stream networks were identified, which demonstrate particular vulnerability to increased withdrawals and their distribution. These are the locations of importance for planners and regulators who oversee water permitting, to reach a sustainable management of the water resources under changing conditions of energy and corresponding water demand.

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1. Introduction

Unconventional natural gas production from shale formations provides a significant domestic energy source in the United States (U.S. Energy Information Administration, 2011). Natural gas extraction from tight geologic formations has increased due to technological advancements of horizontal drilling, leading to economic viability of previously untapped reserves (U.S. Department of Energy, 2009). The potential expansion of high-volume hydraulic fracturing (HVHF) of the Marcellus and Utica Shale into New York State to extract natural gas resources is a controversial issue for policy makers, industry stakeholders, and community members. Issues surrounding this debate range from socioeconomic to logistic to environmental, with emphasis on water quality dictating the direction of scientific research and media attention.

Recently, other environmental concerns associated with HVHF in New York have come to the forefront of discussion. This includes a water quantity perspective, which is traditionally less critical in regions that have ample freshwater supplies in humid climates and/or large, proximate freshwater bodies (Rahm and Riha, 2012). HVHF requires large volumes of water which will ultimately increase water demand from the regions that will experience development. Increased water demand will prompt regulators to determine from where, and at what rate, this water should be extracted to protect sustainable use for drinking water, agriculture, and other industry demands. Altered stream geochemistry and consequences to stream ecosystems, as a result of decreased stream discharge, are factors beyond the anthropogenic freshwater demands mentioned above that may merit consideration. Although water budgets from the New York State Department of Environmental Conservation (NYSDEC) demonstrate that increased water demands from HVHF in New York would make up a minor fraction of total water use (NYSDEC, 2011), it is unclear how hydraulically linked groundwater–surface water systems might respond to such a development. Water budgets alone may not be sufficient in predicting the spatially variable response of these systems, particularly in identifying areas which present heightened sensitivity to withdrawals. For example, the response of aquifers and streams to increased withdrawals of water might vary as a function of valley width, thickness and depth of aquifers within the valley fill. Additionally, smaller streams might be vulnerable to induced changes in groundwater discharge during drought.

The projected path of HVHF development of the Marcellus Shale in New York will most likely focus on the Southern Tier of the state, including Broome and Tioga counties (Fig. 1). The major valleys within these counties overlie an unconsolidated glacial valley-fill aquifer network which has been classified as a sole source aquifer since 1985 (U.S. Environmental Protection Agency, 2010). Such a designation emphasizes the importance of this groundwater source to the overlying municipalities, which receive more than half of their drinking water from the aquifer. In this region there is a high degree of hydraulic connectivity between streams and underlying unconsolidated glacial deposits (Randall, 1977; Wolcott and Coon, 2001; Yager, 1993). High-volume withdrawals of water from groundwater may elicit a response from surface water, or vice versa, due to their physical connectivity (Winter et al., 1998). It is therefore necessary to investigate how different development scenarios might affect both the water table and stream flow.

This research focuses on the use of groundwater flow modeling to determine if increased water demand associated with HVHF is enough to cause significant change to groundwater levels and stream flow within the study area. The objective of this research is to identify scenarios and locations that are particularly vulnerable to high-volume withdrawals of water and may require further evaluation should water permits be requested. A simulated range of development scenarios demonstrate how varying well pad density, water source, and water volume might affect the groundwater–surface water systems in the Southern Tier of New York. The importance of this research lies in its application to all stakeholders in the HVHF controversy currently underway in New York. Not only will policy makers and regulators benefit from the predictive capacity of computer modeling, but industry, community members and interest groups can better understand how a water quantity perspective is valuable for sustainable energy development.

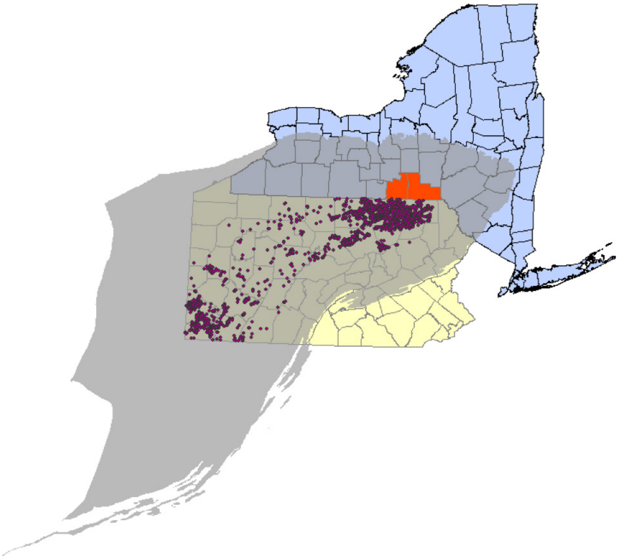

Fig. 1. Marcellus Shale extent across New York and Pennsylvania is highlighted in gray (modified from the U.S. Energy Information Administration and the U.S. Census Bureau). Horizontal wells drilled in the Marcellus Shale in Pennsylvania are in purple and demonstrate the projected path of HVHF in New York State (data from fractracker.org, source: Pennsylvania Department of Environmental Protection). Broome and Tioga counties are highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Background

Hydraulic fracturing is a process that involves the injection of water into the subsurface in order to fracture tight geologic formations. Fracturing creates pathways through which trapped natural gas flows freely into a well and is subsequently harnessed for energy. The combination of hydraulic fracturing and horizontal drilling has led to the growing viability of unconventional shale plays (U.S. Department of Energy, 2009). Horizontal drilling refers to the lateral drilling of a well bore through a target formation. This allows access to a greater volume of gas-bearing rock, making such drilling ventures economically feasible (Soeder, 2010). In HVHF, large volumes of water in addition to proppants and other additives serve as the fracturing fluid. The fluid injection and fracturing process progresses in stages along the horizontal extent of the well, with each horizontal well requiring between 1 and 5 million gallons of water (Gregory et al., 2011). Only a fraction of injected fluid actually returns to the surface – referred to as flowback – with the unreturned volume remaining in the subsurface. This fraction can vary greatly between wells, company, and target formation with an estimated average of 10–40% flowback (Maloney and Yoxtheimer, 2012; NYSDEC, 2011; Rassenfoss, 2011).

In arid climates, where freshwater supply is limited, the quantity of water use associated with HVHF is of concern (Nicot and Scanlon, 2012). In humid climates, where freshwater supply is less emphasized in water resource management, increased water demand associated with HVHF is only beginning to receive recognition (Rahm and Riha, 2012). This is in part due to mass balance or water budget approaches in quantifying the impacts of HVHF water demands. Nicot and Scanlon (2012) estimate water use associated with HVHF is less than 1% of water use in Texas, but may account for larger fractions of water use at the county scale. For example, within the Barnett Shale play in Texas, the 2008 fraction of shale gas water use in the counties of Denton, Johnson, Parker, Tarrant, and Wise was 2.8%, 29%, 10%, 1.4%, and 19%, respectively (Nicot and Scanlon, 2012). Such an investigation emphasizes the numerical insignificance of increased water use from the shale gas industry at a statewide scale, although simultaneously recognizing localized (county-scale) significance. The NYSDEC (2011), estimates that HVHF development would increase water demand by 0.24%. While it is important to acknowledge that an increase of less than 1% of increased water demand is small, localized impacts should not be ignored. Groundwater flow modeling offers a different approach to evaluating increased water demand in the Southern Tier of New York State. This approach captures both regional and localized impacts while complying with the dynamic relationship between stream flow and groundwater.

The NYSDEC (2011) predicts a peak development of 2462 wells in one year across the state of New York, with four wells most likely developed on one well pad. It is also estimated that about 2.4 to 7.8 million gallons (Mgal) will be used for each horizontal well. Accounting for the recycling of flowback water, approximately 3.6 Mgal of freshwater for each horizontal well will be required, assuming that 15% of the average demand of 4.2 Mgal is recycled flowback water (NYSDEC, 2011). These projections are the basis for setting up the range of development scenarios to simulate in this research. In addition to well density and water volume, water source is also included in the development scenarios. Although surface water may be the most likely source (NYSDEC, 2011), municipal pumping wells in Pennsylvania do provide some of the water used in HVHF (Rahm and Riha, 2012). Therefore, both groundwater and surface water are accounted for as potential water sources in the development scenarios. Accounting for both groundwater and surface water withdrawals makes this type of investigation applicable to the HVHF development in the short-term as well as future potential long-term changes in water resources, which may involve surface and groundwater.

3. Site characterization

The aquifer network that underlies Broome and Tioga counties is part of a complex glacial valley-fill system (Fig. 2). The glacial sediments are a legacy of the Late Wisconsin stage of the last Pleistocene glaciation (Aber, 1980; Scully and Arnold, 1981), deposited approximately 16,650 years ago (Cadwell, 1973). The aquifer is composed primarily of ice contact deposits overlain by glacial outwash, which was deposited via meltwater streams (Randall, 1978). The unconsolidated glacial deposits, mainly silty sand and gravel, overlie a thin, discontinuous till, which is underlain by fractured, noncalcareous Devonian bedrock (Scully and Arnold, 1981). Geographically discontinuous lacustrine silt and clay overlie

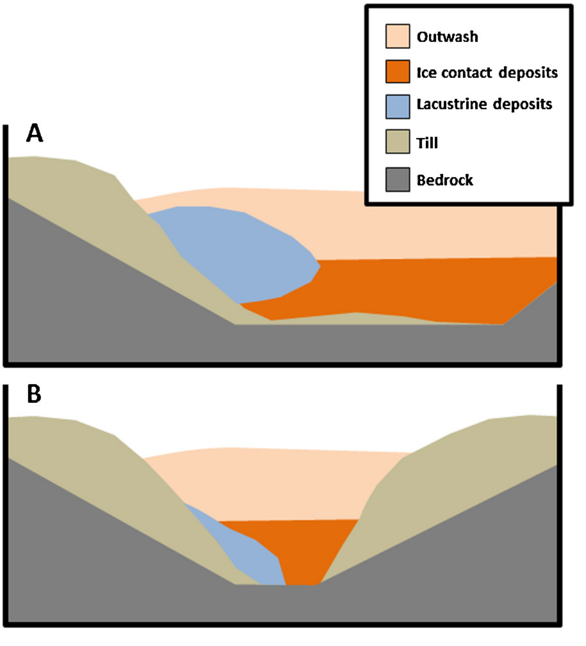

Fig. 2. Generalized, conceptual cross-sections of a wide (A) and a narrow glacial valley (B) (modified from Randall, 2001).

ice-contact deposits, generating confined aquifers in parts of the network (MacNish and Randall, 1982; Randall, 1978, 1986).

Previous work within the proposed study area has clearly defined the depositional history, hydrologic properties, and hydrostratigraphy of the aquifer network (Fleisher, 1986; Kontis et al., 2004; Randall, 1972, 1978, 2001; Reynolds and Williams, 1988; Waller and Finch, 1982). Furthermore, portions of the aquifer network, particularly sections which underlie of metropolitan area of Binghamton in Broome County, New York, have been previously modeled (Coon et al., 1998; Randall, 1986; Wolcott and Coon, 2001; Yager, 1986, 1993). Considering the extent to which gas ventures will most likely expand, it is desirable to extend the modeled areas to simulate the regional flow paths throughout Broome and Tioga counties.

Within these counties there is a high degree of hydraulic connectivity between streams and the underlying aquifer (Randall, 1977; Wolcott and Coon, 2001; Yager, 1993). Additionally, pumping induced recharge from streambed infiltration is significant in the study area (Kontis et al., 2004; Randall, 2001). If municipal pumping rates increase, it becomes important to account for the possibility of added induced recharge. Conversely, groundwater discharge from stratified drift aquifers is the main source of base flow to streams during periods of drought (Randall, 2010). Increased groundwater pumping rates, therefore, would commonly reduce aquifer discharge to streams resulting in reduced stream flow (Randall et al., 1988), although a few broad valleys are drained only by small streams of local origin.

4. Methods

The most significant groundwater flow occurs within the broad valley drift aquifers, limited to the main glacial valleys. Major streams in this setting are parallel to the axes of the valley walls and would not help to constrain the hydrologic boundaries for groundwater flow. Because there are limited natural hydrologic features for use as boundary conditions, a two-dimensional watershed scale analytic element model (Jankovic and Barnes, 1999) was first constructed in Visual AEM (Craig and Matott, 2009) to develop boundary conditions for the localized area of interest (Hunt et al., 1998). The scope of the first model encompasses the Upper Susquehanna River basin, including the valleys of Broome and Tioga counties. Using constant head boundary conditions from Visual AEM, a three-dimensional finite difference MODFLOW model (Harbaugh, 2005) was built to focus on the valleys of interest (Fig. 3). The extracted constant head boundaries were placed along the perimeter of the model extent and are significant in their simulation of upland recharge to the valley-fill aquifer network. Furthermore, the analytic element model was calibrated to real-time stream discharge measurements in order to approximate net regional groundwater recharge.

The finite difference grid was set up in Groundwater Vistas Version 6 (Rumbaugh and Rumbaugh, 2011). The grid is comprised of 193 rows and 281 columns of 250 m × 250 m cells, with a total surface area of approximately 3390 km^2 (Best, 2013). The model contains five layers in order to represent the

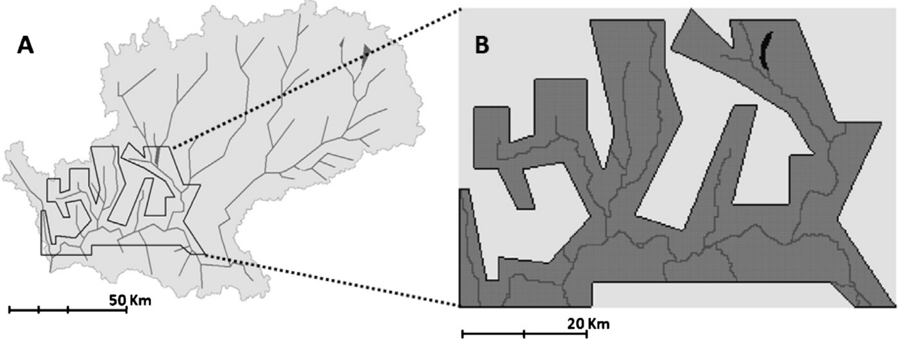

Fig. 3. Diagram illustrating the scale transition from the analytic element model (A) to the finite difference model (B).

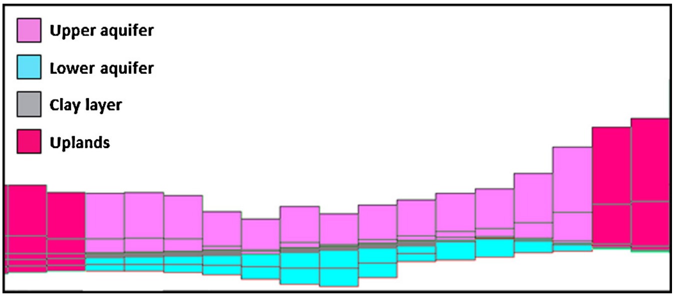

Fig. 4. Cross-section illustrating the model layers and hydraulic conductivity zones derived from the conceptual valley stratigraphy.

hydrostratigraphy of the glacial drift while maintaining the reasonable level of simplicity needed to address the research question from a regional perspective. The top elevation of the uppermost layer represents the land surface and was approximated using an imported and resampled digital elevation model. The bottom elevation of the fifth layer represents the bedrock surface, thereby constraining flow within the valley fill thickness ranging between 3 and 120 m thick. The bedrock surface was interpolated from available well logs, both in published literature (Randall, 1972) and public records from NYSDEC. The first upper two layers of the model represent the unconfined aquifer system. The third layer is a clay unit, which serves to confine the lowest two layers. The thickness and elevation of the third layer was also interpolated from well logs (Randall, 1972). Both aquifer systems – upper and lower – were split into two layers apiece, with their interlayer elevation set at half of the aquifer thickness in each cell.

There are four hydraulic conductivity units in this model (Fig. 4). The uplands are considered one homogeneous, low-conductivity unit, primarily serving as a transmitting media between the external boundary conditions and the valley walls. Separate hydraulic conductivity units were assigned to the upper and lower aquifer systems. Cells representing the clay confining unit were assigned to the fourth conductivity field. Any cell in the third layer with a thickness greater than 3 m is considered part of the confining unit. The remainder of the third layer, where the confining unit is thin or absent, is part of the upper aquifer hydraulic conductivity unit. Manual calibration indicated that this model was not significantly sensitive to conductivity of the confining unit in layer three at the regional scale. Although there is extensive heterogeneity within the valley drift sequences, it is difficult to capture such a variability at this scale. Therefore, these hydraulic conductivity values better represent regional, effective conductivity. Uniform recharge of 62 mm/year was applied to the top of the model, representing the component of groundwater recharge derived from the infiltration of precipitation falling directly in the valleys. This value was approximated by adding the total volume removed from the system (through municipal pumping) to the net regional recharge estimated from the analytic element model (Best, 2013). Constant head boundaries on the outside of the active model area provide the lateral aquifer recharge derived from overland runoff, tributary infiltration, and interflow. In the baseline model, the constant head contribution to groundwater inflow from the boundary of the model was approximately 42%. Constant head contributions in the withdrawal scenarios were evaluated to ensure that this fraction of groundwater input did not unrealistically increase, results of which will be discussed in the sensitivity analysis. The Streamflow-Routing Package (Prudic et al., 2004) was used to simulate stream flow within the model domain. This package allows for the exchange of water between the stream and the aquifer as well as the passage of water between stream cells.

The inverse modeling approach required calibration of hydraulic conductivity for each designated field to 53 head targets. These head targets come from a variety of sources including USGS real-time wells and various one-time head measurements from the NYSDEC water well program, consulting reports, field work, and mine data. Assuming isotropy, hydraulic conductivity was varied according to improvements in root mean squared error (RMSE). The final RMSE was 7.08 m with the range of observed water level variability across the model domain from 215.5 m above sea level to 364.7 m above sea level. This error was considered acceptable due to the large model extent, the coarse cell size, and the simplified heterogeneity. The resolution that can be expected for any model must be reflective of that model's scale. Secondly, the largest residuals are generally located near external boundaries. The boundary conditions, therefore, are controlling the sensitivity of those targets to changes in hydraulic conductivity. Lastly, this research is only investigating the differences between the baseline model and scenario simulations. Such a comparison requires less certainty in absolute values of the baseline model because the error is linearly transferred to the applied scenario models.

5. Development scenarios

While there are some projections of HVHF development in New York (Davis and Robinson, 2012; NYSDEC, 2011), it is difficult to definitively predict well pad density, the particular source water that will be used, and the volume of water required for each pad. This research required the design and testing of a range of potential development scenarios to produce meaningful simulations. These development scenarios are not predictive but serve as an objective quantification of possible increased water demand. Three variables were included in each scenario: well pad density, source of water for each well pad, and volume of water per well pad. Although the time over which water is extracted is in fact an important variable, this research distributes all water withdrawals over an entire year using a steady state modeling assumption. As a result of the steady state assumption, boundary conditions represent the average annual flow that enters, and exits the model domain. This is to avoid the associated uncertainty with the time variable and the added modeling complexity in introducing model transience.

5.1. Well pad density

Well pad density is the percentage of land developed for natural gas extraction. For this research, instead of considering the impact of individual wells, well pads – upon which multiple wells may be drilled – are assumed to be the trending mode of development. This document uses "unit" to describe the surface area encompassing both the well pad and the wells' underground horizontal extent. Each unit can have one well pad, again accommodating multiple wells. Because of this distinction, well spacing requirements are not addressed in this configuration. Land use and land coverage are the limiting factors in delineating available land for development (Fig. 5). Regulations currently proposed (NYSDEC, 2013) would limit the density of well pads to no more than one pad per square mile. At each pad as many as 9 horizontal wells would be allowed. Accordingly, the study area was subdivided into a grid of 1-square-mile (2.6 km^2) units (Fig. 5A). Any unit that overlaps NYSDEC land was excluded. Units were then further excluded based on the percentage of land which is considered "unavailable", including wetlands, open water, and developed/urban areas. Any unit with greater than 75% unavailable land was next excluded. Of the remaining units, some percentage was selected to represent the density of development across the modeled extent for that particular scenario. The range of development density simulated is between 5% and 20%. Selection from the available units was based on a regular distribution scheme that required numbering of the units. The first unit is located in the bottom left of the model extent and the numbering continues from left to right and from bottom to top. A 10% development density, for example, would use one out of every 10 units in the grid (Fig. 5D).

5.2. Water source

Both groundwater and surface water were considered potential water sources in this research. Groundwater is pumped from either municipal wells or new, privately operated wells, the latter of which will be referred to as the distributed pumping source hereafter. Surface water withdrawals are taken directly from streams. The location of each source, or the point of withdrawal, was determined using a Euclidean allocation function. This function locates the closest straight-line distance from each well pad to each source type (Fig. 6). Every well pad, therefore, has a closest municipal pumping source, distributed pumping source, and stream source. While the closest stream source was selected based on shortest distance, the point of withdrawal was applied at the end of that stream segment at the point of

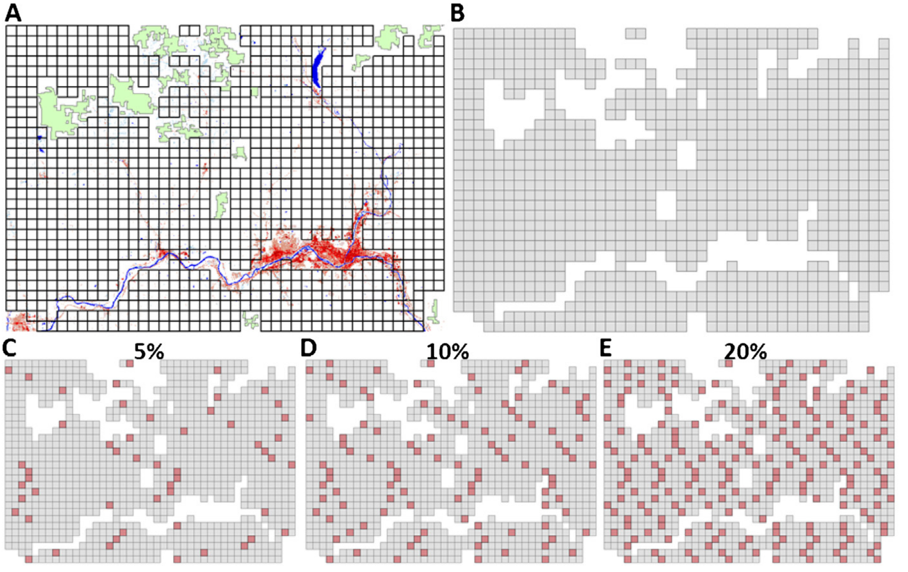

Fig. 5. Illustration of density schemes. The exclusion process (A) considered NYSDEC lands (green), open water (dark blue), wetlands (light blue), and urban areas (shades of red). Of the available units (B), different densities were selected using an even distribution. Results for (C) 5%, (D) 10%, and (E) 20% development density scenarios are presented in this paper. Selected units are in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

confluence with the next converging stream. A source combination was also included in the scenario runs; this option allowed each well pad to take half of its required water from its designated municipal source and half from its designated stream source. Although it is unlikely that private groundwater wells will be the primary source of HVHF water, this research attempts to simulate a range of water supply options to not only quantify the potential changes but further understand the sensitivity of this hydrologic system to high-volume withdrawals. If groundwater wells are selected to supply water for HVHF, it should be noted that the locations of those wells would likely be chosen based on their anticipated pumping capacity; because the allocation of water source in this project considered any valley cell as a potential pumping location (weighted equally), the pumping capacity and productivity of wide as opposed to narrow valleys was not included. These development scenarios are not intended to predict the potential locations of future groundwater wells.

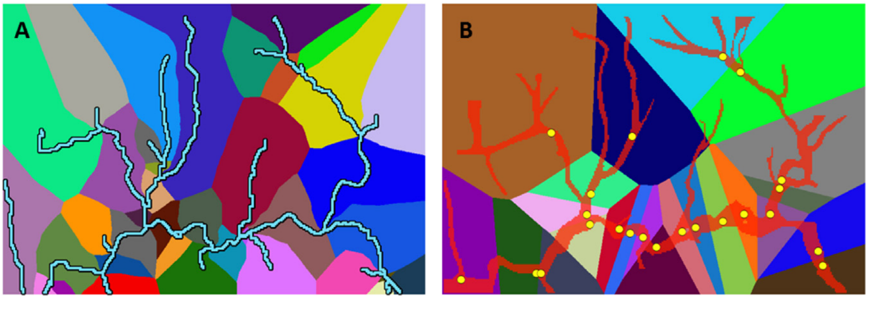

Fig. 6. Allocation of water source based on a Euclidean function. For each unit, the nearest water source was designated based on proximity to the nearest stream for a stream source (A) and nearest municipal pumping center for a municipal groundwater source (B), indicated by yellow circles. Distributed pumping locations were determined in the same manner using distance to the nearest cell in a valley. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. Water volume

The volume of water required for each well pad is the product of the number of wells developed on the site and the volume of water each well requires. Between 4 and 9 wells could be accommodated on each well pad based on New York spacing requirements. Approximately 3–4 Mgal of water is required for each well according to predicted averages (NYSDEC, 2011); these volumes account for the fraction of injected water which may be derived from the flowback of previously developed wells. In these simulations, between 12 and 32 Mgal of water represents the range of possible water volumes withdrawn for each well pad. This range allows flexibility in the absolute number of wells or volume of water required per well. For example, if 4 wells are developed on a well pad with each using 8 Mgal of water, the maximum water volume in the scenario range is met. If 8 wells are developed on a well pad with each using 4 Mgal of water, the maximum water volume in the scenario range is likewise met.

5.4. Simulation and comparison

There are two modes of comparison between the baseline model and the various withdrawal scenarios. The baseline model simply refers to the calibrated MODFLOW model in which current pre-development pumping conditions are at steady-state, while the various withdrawal scenarios are individual models with different pumping/withdrawal conditions applied to each. Pre-development pumping refers only to current rates of groundwater pumping from municipal water supply wells. Any change in the water table will be evaluated in the form of a head difference map – hydraulic head in every model cell in the scenario simulation is subtracted from its counterpart in the baseline model. Every cell in the model domain is therefore attributed a number, with positive values indicating a rise in the water table across that cell and negative values indicating a decline in the water table across that cell. No change to the water table after pumping/withdrawal simulations is interpreted from any zero-value cell in the model domain. Additionally, any cell with a value within 25 cm of zero change was also considered no change due to model variability. The second mode of comparison between the baseline model and the various scenario simulations is the percent change in stream flow. As a result of uniform groundwater recharge under the steady state modeling assumption any change in stream flow under a given development scenario represents the change in groundwater discharge to streams, or base flow. Although surface water modeling would emphasize change to total stream flow, assessing percent change through this technique does not depend absolutely on the accuracy of stream flow in the baseline model. In this way, changes to both the water table and stream flow as a result of either groundwater pumping or stream withdrawal are quantified.

6. Results and discussion

6.1. Potential effects on the water table

Results of this research indicate that changes to groundwater levels are minimal at low development densities and with low water volumes extracted for each pad. Simulated development scenarios demonstrate locally increasing drawdown with increasing development density at a set volume of water per pad (12 Mgal, Fig. 7). In this case, the water used for HVHF is from a combination of both municipal groundwater and stream water. Other models in this research, which simulate withdrawals from distributed pumping wells and streams, mirror the positive relationship between increased development density and drawdown. Assuming the well pad density is constant, increasing the volumes of water extracted for each well pad likewise increases drawdown. One of the main differences between the sources, however, is the spatial distribution of withdrawals and the subsequent concentration or dispersal of water level change (Fig. 8). It is clear that groundwater levels throughout the model domain experience no detectable change from stream withdrawals. Groundwater withdrawals, however, have spatially discrete effects on the water table, while the rest of the model area remains unchanged. The few areas experiencing drawdown in the municipal pumping and combination source scenarios are directly adjacent to municipal pumping wells. With increasing withdrawal,

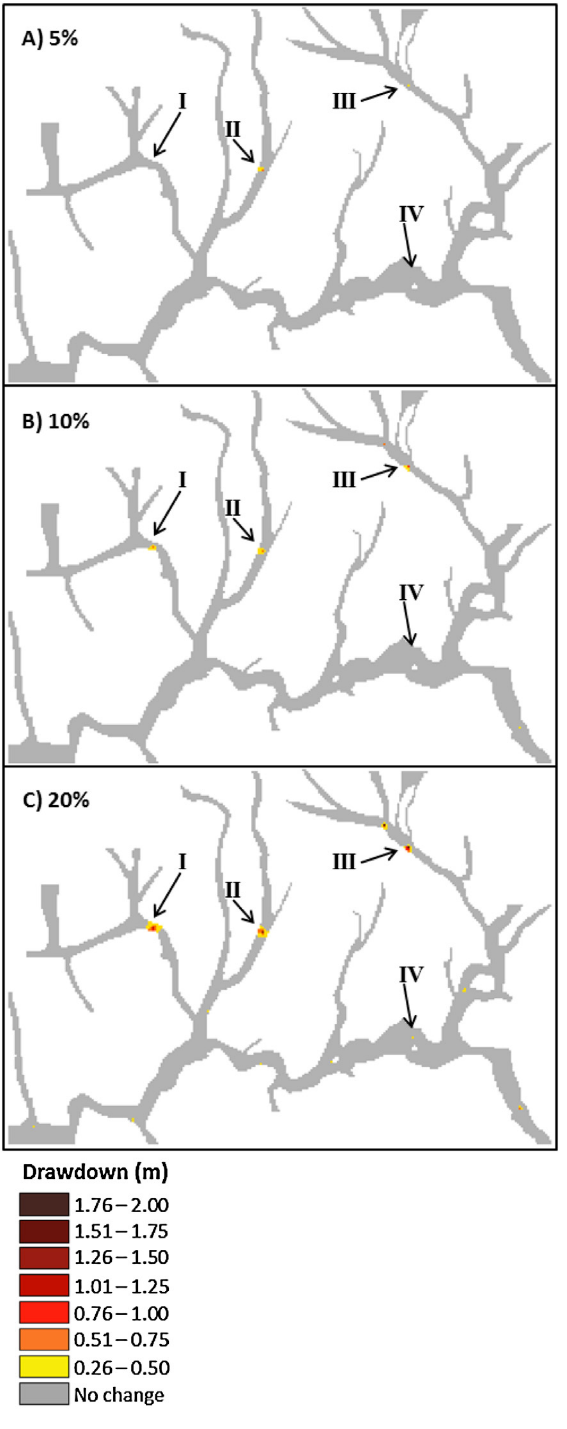

Fig. 7. Simulated drawdowns near municipal wells, assuming half the water use at each HVHF pad is pumped from municipal wells and half from streams. Although water volume per pad is constant at 12 Mgal, development density increases A to C. Note locations labeled I–IV, referred to in text.

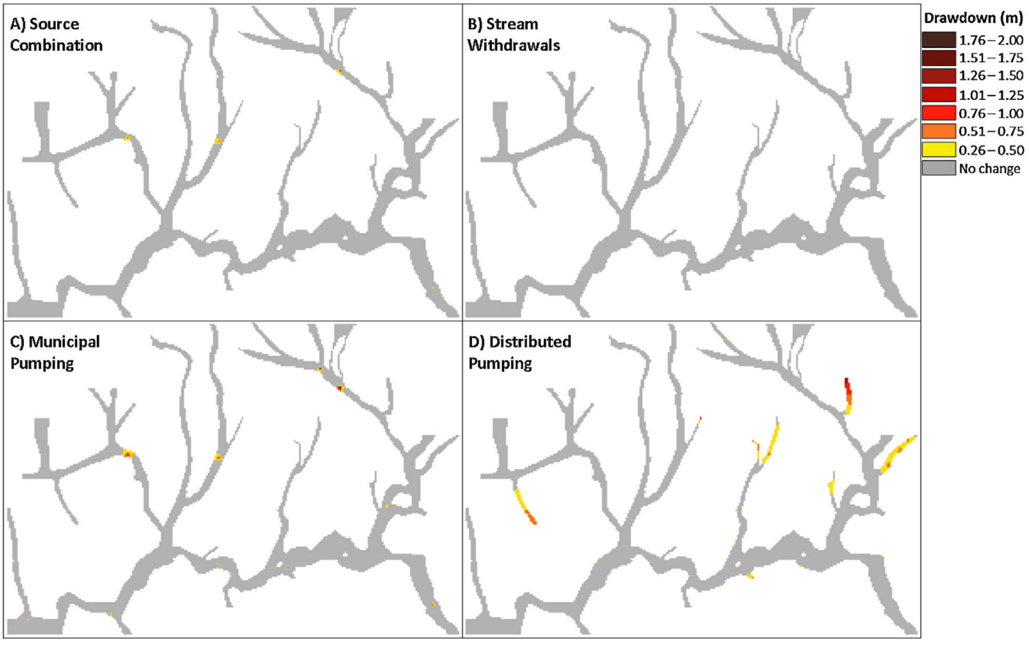

Fig. 8. Head difference maps for 10% development density scenarios with 12 Mgal of water extracted for each well pad. Each frame displays results of using different water sources: (A) combination of municipal pumping and stream withdrawal, (B) stream water only, (C) municipal pumping only, and (D) distributed pumping.

the cones of depression at municipal wells in narrow glacial valleys are both expanded and deepened (Fig. 7, locations I–III). Municipal wells located in the widest glacial valleys and near major rivers, particularly the Susquehanna River, do not experience the same impact (Fig. 7, location IV). The municipal pumping and combination source scenarios produce the same spatial distribution of water table change although there is a difference in the magnitude of change. A distributed pumping source evokes the most widespread drawdown although the extent of drawdown is still limited to narrow valleys (Fig. 8D).

Groundwater levels are relatively insensitive to increased water withdrawals although there are two exceptions. First, greater cones of depression are notable around municipal wells when pumping rates increase (Fig. 7). When the burden of water source is instead split between streams and municipal wells, the effect on the water table is lessened. Vulnerable municipal wells appear to be associated with narrow valleys (Fig. 8C). This may be a result of aquifer geometry, area of contributing recharge, and availability of induced recharge from streams. Aquifer geometry refers to both the width and depth of glacial valley fill. The pumping center near Binghamton, NY (Fig. 7, location IV) is an example of a region within the valley aquifer that has municipal wells with the capacity to accommodate the increased pumping rate. These wells are located in a wide valley with thick aquifer deposits. Additionally, proximity to a large stream allows the possibility for greater induced recharge from the stream. The second susceptibility occurs under distributing pumping conditions, during which significant reductions in groundwater elevations are apparent in narrow valleys (Fig. 8D). Again, this is most likely associated with the aquifer geometry and area of contributing recharge.

As demonstrated in Fig. 7, increases in both development density and water volume per pad elicit heightened water table responses; this trend was shared by all sources. Although water table change was still undetectable for stream withdrawals at the maximum development tested, heightened resolution and smaller scale models might allow for better understanding of the connection between streams and groundwater.

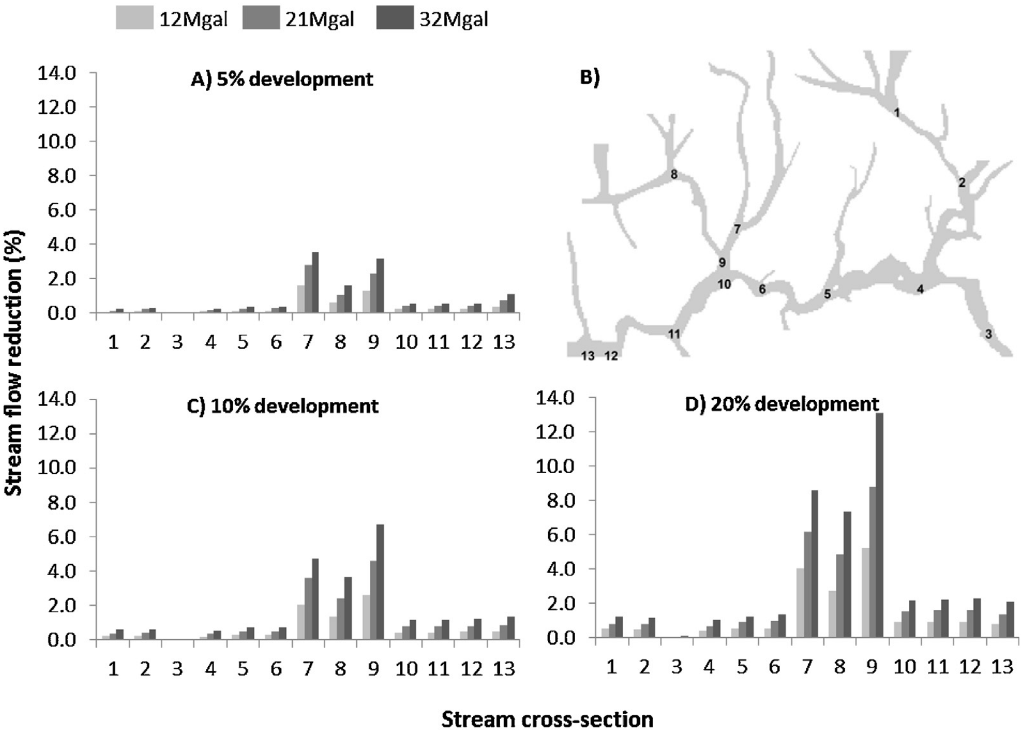

Fig. 9. Percentage of stream flow reduction at points along the stream network. The results shown are from scenarios extracting from a combination of municipal pumping wells and streams. The polygon (B) delineates the aquifer network with the numbers indicating the locations at which stream flow was compared (referred to as stream cross-section). Variations in both development density and water volume per pad are given in each bar graph.

6.2. Potential effects on stream flow

Changes to stream flow in response to high-volume water withdrawals are spatially variable. The most significant reduction to stream flow is concentrated in one region of the model (Fig. 9, cross-sections 7, 8, and 9). Other areas of the model respond relatively uniformly to extraction scenarios, with the percent reduction in stream flow increasing with increasing development density and water volume per pad. Within the minimum development range, extracting water from both municipal pumping wells and streams reduces stream flow by less than 2% throughout most of the stream network (Fig. 9A). At the maximum density of development, stream flow is reduced by up to 13% in a localized region (Fig. 9D). Under those same development conditions, however, stream flow reduction still remains under 3% throughout most of the stream network. Although the magnitude of stream flow reduction changes based on water source, the general spatial distribution persists (Fig. 10). Streams throughout the model respond consistently to applied withdrawal scenarios with the exception of stream cross-sections 7, 8, and 9, which exhibit nearly three times the stream flow reduction as compared to the rest of the stream segments. The combination source and stream withdrawals produced the greatest response in stream flow whereas distributed pumping scenario results in a less dramatic response (Fig. 10). Extracting from municipal wells causes more spatial variability in stream flow reduction as compared to the combination source (Fig. 10, cross-section 8).

There is a positive relationship between stream flow reduction and volume of extracted water which is determined by both well pad density and water volume per pad. Relatively uniform response throughout most of the stream segments emphasizes the markedly greater response at cross-sections

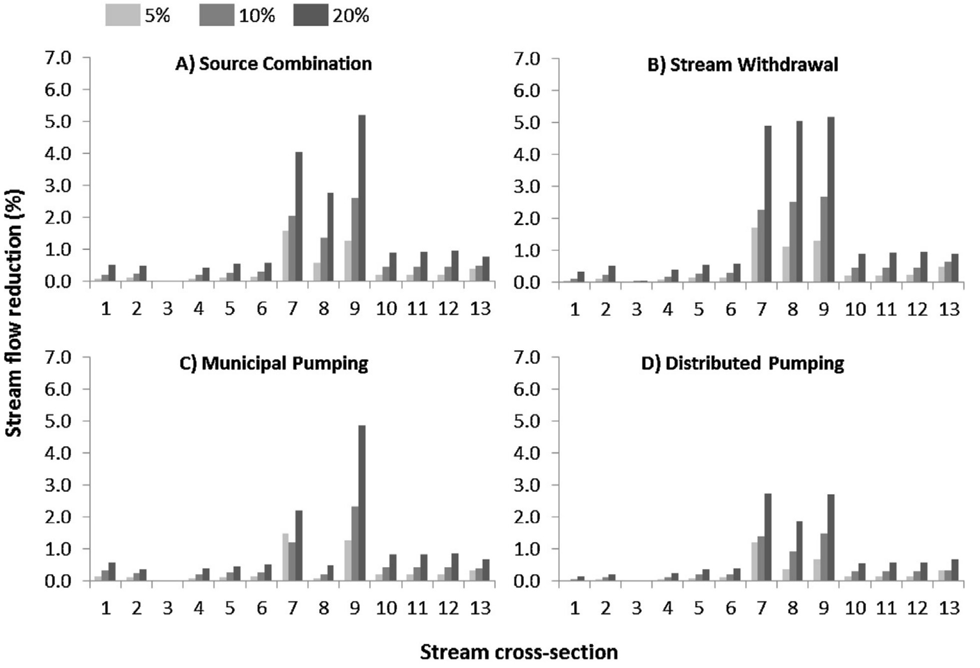

Fig. 10. Stream flow changes as a result of different source water. Stream cross-section refers to the reference map (Fig. 7B). Density of development is a variable in each graph while water volume per pad is constant at 12 Mgal per well pad.

7, 8, and 9 (Fig. 9). These locations are in narrow valleys and represent streams with lesser annual discharge. These two factors dictate the capacity of groundwater–surface water exchange when withdrawals from either the aquifer or the streams are applied. Downstream parts of the stream network (Fig. 9, cross-sections 10–13) demonstrate slightly greater sensitivity to combination source withdrawals than the upstream portion of the model area. This potentially demonstrates how effects from a tributary stream might propagate to the main stream with which it converges. The actual magnitude of stream flow reduction in a high water use scenario may be considered significant only during drought conditions. This underscores the importance of understanding the implications of withdrawal timing and duration on potentially vulnerable valleys. Incorporation of model transience would help address this uncertainty.

The spatial distribution of changes to stream flow is consistent between sources, with the exception of the municipal pumping scenarios (Fig. 10, cross-section 8). This location exemplifies an instance of "shared response" between stream flow and the water table. At this location, the municipal cone of depression is greatest when water is taken only from the municipal well while the stream flow reduction is comparably small. When the burden of water source is shared with withdrawals from the nearby stream, the water table impact is alleviated (Fig. 8A) while the stream flow reduction intensifies (Fig. 10). Intuitively, stream flow is reduced most when water is taken only from the streams. Results demonstrate that the water table is insensitive to stream withdrawals (Fig. 8). It can be inferred that stream–aquifer connectivity distributes the stream withdrawals over a larger area than concentrated pumping schemes, thus resulting in insignificant drawdown. Only when municipal pumping is added (Fig. 10A) water table and stream flow changes simultaneously emerge. Distributed pumping has the least effect on stream flow because of the distribution of water burden. Many low-capacity wells draw uniformly less from overlying streams than fewer high-capacity wells. If stream flow protection is prioritized based on suggested vulnerability, it is important to note that a distributed pumping source causes the least reductions to stream flow.

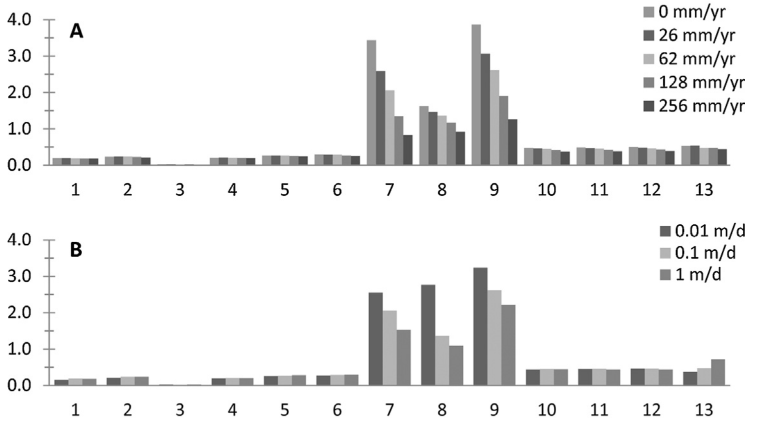

Fig. 11. Sensitivity of model results to (A) groundwater recharge and (B) hydraulic conductivity of streambed sediments. The base case parameters are 0.62 mm/yr and 0.1 m/d for recharge and streambed sediment conductivity, respectively. Density of development is constant at 10% and water volume per pad is constant at 12 Mgal per well pad. The simulated water source is the municipal pumping and surface water combination scenario.

6.3. Sensitivity

There are two aspects of this model that are significant in dictating model results: the volume of water input to the system as a result of aquifer recharge and the connectivity of the aquifer and overlying streams as a result of streambed conductance. In order to determine the impacts of these parameters a sensitivity analysis was conducted. The greatest uncertainty in this model is the value estimated for applied recharge, which is associated with infiltration of direct valley precipitation. Recharge is the main parameter that governs how much water is available to the system. Increasing recharge decreases the percent reduction in stream flow, mainly in areas of the stream network that experience the greatest change (Fig. 11A, cross-sections 7–9). As expected, the greatest reduction to streamflow is identified under zero-recharge, or severe drought, conditions.

The hydraulic connectivity between surface water and groundwater is primarily controlled by streambed conductance. Hydraulic conductivity of streambed sediments is one of the variables that determines streambed conductance. Similar to recharge sensitivity, increasing the streambed sediment conductivity reduces the changes to stream flow (Fig. 11B). Again, this sensitivity is generally apparent at stream segments which experienced the greatest change. It is crucial for water resource management analyses to consider the range of results possible given the sensitivity of results to a particular model feature.

In addition to the evaluation of model sensitivities to the variability in aquifer recharge and streambed conductance, the impact of specified head boundary conditions was evaluated. The model mass balance was analyzed to determine whether constant head contributions to groundwater input would change under withdrawal scenarios. The input volume from the constant head boundary conditions increased by less than 1% for each of the source scenarios at maximum development, with the exception of the distributed pumping case. Distributed pumping induced a 9% increase in the constant head input volume. This volume is less than the applied recharge, which supports the use of constant head boundary conditions at the edge of the model domain. Mass balance results demonstrate that these boundary conditions do not supply unrealistic volumes of water to the aquifer under increased pumping conditions.

7. Conclusions

Although regions that are water-rich encounter fewer water quantity issues as compared to arid regions, possible implications of energy development and subsequent water demands must be considered. This is particularly applicable in areas that have barriers – legal, physical, or economic – to alternate sources of drinking water so both the quality and sustainable supply of existing sources must be safeguarded. Simulating water table and stream flow response to high-volume water withdrawal scenarios is effective in quantifying the potential impacts of increased water demand associated with HVHF expansion into New York State. This research emphasized a regional perspective to first determine whether changes to the water table and/or stream flow could be detected under potential development scenarios. Identification of high-impact scenarios and susceptible model areas demonstrates the utility of regional groundwater flow modeling in assessing a water quantity concern.

The range of development scenarios modeled depict impacts to water resources that are most pronounced at municipal pumping centers and along narrow tributary valleys. Cones of depression would deepen around municipal pumping wells, if postulated HVHF water needs were withdrawn partially or entirely from those wells. Additional drawdown around municipal wells in wide valleys would be negligible. Significant drawdown is simulated in narrow tributary valleys under pumping scenarios that call for HVHF withdrawals from new private wells at valley sites closest to postulated gas wells. Results demonstrate the capacity for increased pumping is constrained by the contributing recharge area and aquifer geometry. Furthermore, there is diminished opportunity for induced recharge in streams within these narrow valleys. At these locations, distributed pumping wells would draw more water from the aquifer than could be replenished by groundwater recharge.

It is important to recognize that both groundwater pumping *and* stream withdrawals have an impact on stream discharge. The greatest stream flow reductions were geographically limited to a particular section of the stream network (Fig. 9, cross-sections 7–9). Valley width appears to be the limiting factor in determining the magnitude of stream flow reduction. Some reductions were detected on larger streams at locations downstream from those particular cross-sections. As a result of the high hydraulic connectivity between the streams and underlying aquifer, water resource management decisions pertaining to HVHF water demands should fully represent the freshwater system as a single resource.

To best understand changes to cones of depression around municipal pumping centers or nearby stream discharge changes, localized fine-scale models are optimal. Furthermore, transient models would allow quantification of variable withdrawal timing and duration. This research presents a necessary foundation for analyzing water resources at a regional scale with the understanding that individual applications would require further high-resolution analysis. Planning and regulation of HVHF will ultimately encounter water permitting decisions. These decisions should conservatively consider the hydraulically connected groundwater–surface water systems, which exhibit spatially distributed sensitivities to high-volume withdrawals.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.05.001.

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